

PROCEEDINGS OF THE
AMERICAN MATHEMATICAL SOCIETY
Volume 00, Number 0, Pages 000–000
S 0002-9939(XX)00000-0

CODES OVER RINGS OF SIZE FOUR, HERMITIAN LATTICES, AND CORRESPONDING THETA FUNCTIONS

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ABSTRACT. Let $K = Q(\sqrt{-\ell})$ be an imaginary quadratic field with ring of integers \mathcal{O}_K , where ℓ is a square free integer such that $\ell \equiv 3 \pmod{4}$ and $C = [n, k]$ be a linear code defined over $\mathcal{O}_K/2\mathcal{O}_K$. The level ℓ theta function $\Theta_{\Lambda_\ell(C)}$ of C is defined on the lattice $\Lambda_\ell(C) := \{x \in \mathcal{O}_K^n : \rho_\ell(x) \in C\}$, where $\rho_\ell : \mathcal{O}_K \rightarrow \mathcal{O}_K/2\mathcal{O}_K$ is the natural projection. In this paper, we prove that: i) for any ℓ, ℓ' such that $\ell \leq \ell'$, $\Theta_{\Lambda_\ell}(q)$ and $\Theta_{\Lambda_{\ell'}}(q)$ have the same coefficients up to $q^{\frac{\ell+1}{4}}$, ii) for $\ell \geq \frac{2(n+1)(n+2)}{n} - 1$, $\Theta_{\Lambda_\ell}(C)$ determines the code C uniquely, iii) for $\ell < \frac{2(n+1)(n+2)}{n} - 1$ there is a positive dimensional family of symmetrized weight enumerator polynomials corresponding to $\Theta_{\Lambda_\ell}(C)$.

1. INTRODUCTION

Let $K = Q(\sqrt{-\ell})$ be an imaginary quadratic field with ring of integers \mathcal{O}_K , where ℓ is a square free integer such that $\ell \equiv 3 \pmod{4}$. Then the image $\mathcal{O}_K/2\mathcal{O}_K$ of the projection $\rho_\ell : \mathcal{O}_K \rightarrow \mathcal{O}_K/2\mathcal{O}_K$ is \mathbb{F}_4 (resp., $\mathbb{F}_2 \times \mathbb{F}_2$) if $\ell \equiv 3 \pmod{8}$ (resp., $\ell \equiv 7 \pmod{8}$).

Let \mathcal{R} be a ring isomorphic to \mathbb{F}_4 or $\mathbb{F}_2 \times \mathbb{F}_2$ and $C = [n, k]$ be a linear code over \mathcal{R} of length n and dimension k . An admissible level ℓ is an ℓ such that $\ell \equiv 3 \pmod{8}$ if \mathcal{R} is isomorphic to \mathbb{F}_4 or $\ell \equiv 7 \pmod{8}$ if \mathcal{R} is isomorphic to $\mathbb{F}_2 \times \mathbb{F}_2$. Fix an admissible ℓ and define $\Lambda_\ell(C) := \{x \in \mathcal{O}_K^n : \rho_\ell(x) \in C\}$. Then, the **level ℓ theta function** $\Theta_{\Lambda_\ell(C)}(\tau)$ of the lattice $\Lambda_\ell(C)$ is given as the symmetric weight enumerator swe_C of C , evaluated on the theta functions defined on cosets of $\mathcal{O}_K/2\mathcal{O}_K$. In this paper we study the following two questions:

- i) How do the theta functions $\Theta_{\Lambda_\ell}(C)$ of the same code C differ for different levels ℓ ?
- ii) Can non-equivalent codes give the same theta functions for all levels ℓ ?

In an attempt to study the second question Chua in [1] gives an example of two non-equivalent codes that give the same theta function for level $\ell = 7$ but not for higher level thetas. We will show in this paper how such an example is not a coincidence. Our main results are as follows:

Theorem 1: *Let C be a code defined over \mathcal{R} . For all admissible ℓ, ℓ' such that $\ell > \ell'$, the following holds*

$$\Theta_{\Lambda_\ell}(C) = \Theta_{\Lambda_{\ell'}}(C) + \mathcal{O}(q^{\frac{\ell'+1}{4}}).$$

2000 *Mathematics Subject Classification*. Primary 11H71, 94B75; Secondary 11H31.

Key words and phrases. Theta functions, Hermitian lattices, codes.

Theorem 2: Let C be a code of size n defined over \mathcal{R} and $\Theta_{\Lambda_\ell}(C)$ be its corresponding theta function for level ℓ . Then the following hold:

- i): For $\ell < \frac{2(n+1)(n+2)}{n} - 1$ there is a δ -dimensional family of symmetrized weight enumerator polynomials corresponding to $\Theta_{\Lambda_\ell}(C)$, where $\delta \geq \frac{(n+1)(n+2)}{2} - \frac{n(\ell+1)}{4} - 1$.
- ii): For $\ell \geq \frac{2(n+1)(n+2)}{n} - 1$ and $n < \frac{\ell+1}{4}$ there is a unique symmetrized weight enumerator polynomial which corresponds to $\Theta_{\Lambda_\ell}(C)$.

This paper is organized as follows. In the second section, we give a basic introduction of lattices and theta functions. We define a lattice Λ over a number field K in general, the theta series of a lattice, and one dimensional theta series and its shadow. Then we discuss the lattices over imaginary quadratic fields $K = \mathbb{Q}(\sqrt{-\ell})$ with ring of integers \mathcal{O}_K , where ℓ is a square free integer such that $\ell \equiv 3 \pmod{4}$. The ring $\mathcal{O}_K/(2\mathcal{O}_K)$ is equivalent to either the field of order 4 or a ring of order 4 depending on whether $\ell \equiv 3 \pmod{8}$ or $\ell \equiv 7 \pmod{8}$. We define bi-dimensional theta functions for the four cosets of $\mathcal{O}_K/(2\mathcal{O}_K)$.

In the third section, we define codes over \mathbb{F}_4 and $\mathbb{F}_2 \times \mathbb{F}_2$, the weight enumerators of a code, and recall the main result of [1]. We simplify the expressions for bi-dimensional theta series and prove Theorem 1.

In the fourth section, we study families of codes corresponding to the same theta function. We call an **acceptable theta series** $\Theta(q)$ a series for which there exists a code C such that $\Theta(q) = \Theta_{\Lambda_\ell}(C)(q)$. For any given ℓ and an acceptable theta series $\Theta(q)$ we can determine a family of symmetrized weight enumerators which correspond to $\Theta(q)$. For small ℓ this is a positive dimensional family, where the dimension is given by Theorem 2, i). Hence, the example given in [1] is no surprise. For large ℓ (see Theorem 2, ii)) this is a 0-dimensional family of symmetrized weight enumerators which correspond to $\Theta(q)$. Therefore, the example that Chua provides can not occur for larger ℓ .

2. INTRODUCTION TO LATTICES AND THETA FUNCTIONS

Let K be a number field and \mathcal{O}_K be its ring of integers. A lattice Λ over K is an \mathcal{O}_K -submodule of K^n of full rank. The Hermitian dual is defined by

$$(2.1) \quad \Lambda^* = \{x \in K^n \mid x \cdot \bar{y} \in \mathcal{O}_K, \text{ for all } y \in \Lambda\},$$

where $x \cdot y := \sum_{i=1}^n x_i y_i$. In the case that Λ is a free \mathcal{O}_K -module, for every \mathcal{O}_K basis $\{v_1, v_2, \dots, v_n\}$ we can associate a Gram matrix $G(\Lambda)$ given by $G(\Lambda) = (v_i \cdot v_j)_{i,j=1}^n$ and the determinant $\det \Lambda := \det(G)$ defined up to squares of units in \mathcal{O}_K . If $\Lambda = \Lambda^*$ then Λ is Hermitian self-dual (or unimodular) and integral if and only if $\Lambda \subset \Lambda^*$. An integral lattice has the property $\Lambda \subset \Lambda^* \subset \frac{1}{\det \Lambda} \Lambda$. An integral lattice is called even if $x \cdot x \equiv 0 \pmod{2}$ for all $x \in \Lambda$, and otherwise it is odd. An odd unimodular lattice is called a Type 1 lattice and even unimodular lattice is called a Type 2 lattice.

The theta series of a lattice Λ in K^n is given by $\Theta_\Lambda(\tau) = \sum_{z \in \Lambda} e^{\pi i \tau z \bar{z}}$, where $\tau \in H = \{z \in \mathbb{C} : \text{Im}(z) > 0\}$. Usually we let $q = e^{\pi i \tau}$. Then, $\Theta_\Lambda(q) = \sum_{z \in \Lambda} q^{z \bar{z}}$. The 1-dimensional theta series and its **shadow** are given by

$$(2.2) \quad \theta_3(q) := \sum_{m \in \mathbb{Z}} q^{m^2}, \quad \theta_2(q) := \sum_{m \in \mathbb{Z}+1/2} q^{m^2}.$$

Let $\ell > 0$ be a square free integer and $K = Q(\sqrt{-\ell})$ be the imaginary quadratic field with discriminant d_K . Recall that $d_K = -\ell$ if $\ell \equiv 3 \pmod{4}$ and $d_K = -4\ell$ otherwise.

Let \mathcal{O}_K be ring of integers of K . The Hermitian lattice Λ over K is an \mathcal{O}_K - submodule of K^n of full rank. Let $\ell \equiv 3 \pmod{4}$ and d be a positive number such that $\ell = 4d - 1$. Then, $-\ell \equiv 1 \pmod{4}$. This implies that the ring of integers is $\mathcal{O}_K = \mathbb{Z}[\omega_\ell]$, where $\omega_\ell = \frac{-1+\sqrt{-\ell}}{2}$ and $\omega_\ell^2 + \omega_\ell + d = 0$. The principal norm form of K is given by $Q_d(x, y) = |x - y\omega_\ell|^2 = x^2 + xy + dy^2$. Since $\ell \equiv 3 \pmod{4}$, we can consider two cases:

(1) If $\ell \equiv 3 \pmod{8}$ then $-\ell \equiv 5 \pmod{8}$. Thus, the prime ideal $\langle 2 \rangle \subset \mathbb{Z}$ lifts to a prime $2\mathcal{O}_K \subset \mathcal{O}_K$. Since the ring of integers \mathcal{O}_K is a Dedekind domain, $2\mathcal{O}_K$ is a maximal ideal. Therefore $\mathcal{O}_K/(2\mathcal{O}_K) \simeq \mathbb{F}_4$.

(2) If $\ell \equiv 7 \pmod{8}$ then $-\ell \equiv 1 \pmod{8}$. Then the prime ideal $\langle 2 \rangle \in \mathbb{Z}$ splits in K . Therefore $2\mathcal{O}_K$ splits in \mathcal{O}_K . Hence, $\mathcal{O}_K/(2\mathcal{O}_K) \simeq \mathbb{F}_2 \times \mathbb{F}_2$. In either case, a complete set of coset representatives is $\{0, 1, \omega_\ell, 1 + \omega_\ell\}$.

Let the following be the bi-dimensional theta series for the four cosets:

$$\begin{aligned}
 (2.3) \quad A_d(q) &:= \Theta_{2\mathcal{O}_K}(\tau) = \sum_{m,n \in \mathbb{Z}} q^{4Q_d(m,n)} \\
 C_d(q) &:= \Theta_{1+2\mathcal{O}_K}(\tau) = \sum_{m,n \in \mathbb{Z}} q^{4Q_d(m+\frac{1}{2}, n)} \\
 G_d(q) &:= \Theta_{\omega_\ell+2\mathcal{O}_K}(\tau) = \sum_{m,n \in \mathbb{Z}} q^{4Q_d(m, n+\frac{1}{2})} \\
 H_d(q) &:= \Theta_{1+\omega_\ell+2\mathcal{O}_K}(\tau) = \sum_{m,n \in \mathbb{Z}} q^{4Q_d(m+\frac{1}{2}, n+\frac{1}{2})}
 \end{aligned}$$

Then we have the following lemma.

Lemma 1. *Bi-dimensional theta series can be further expressed in terms of the standard one dimensional theta series and its shadow.*

$$\begin{aligned}
 (2.4) \quad A_d(q) &= \theta_3(q^4)\theta_3(q^{4\ell}) + \theta_2(q^4)\theta_2(q^{4\ell}) \\
 C_d(q) &= \theta_2(q^4)\theta_3(q^{4\ell}) + \theta_3(q^4)\theta_2(q^{4\ell}) \\
 G_d(q) &= H_d(q) = \frac{\theta_2(q)\theta_2(q^\ell)}{2}.
 \end{aligned}$$

Moreover,

$$(2.5) \quad 2G_d(q) = A_d(q^{1/4}) - A_d(q) - C_d(q).$$

Proof. See [3] for details. □

3. CODES OVER \mathbb{F}_4 AND $\mathbb{F}_2 \times \mathbb{F}_2$

Let $\mathbb{F}_4 = \{0, 1, \omega, \omega^2\}$, where $\omega^2 + \omega + 1 = 0$, be the finite field of four elements. The conjugation is given by $\bar{x} = x^2$, $x \in \mathbb{F}_4$. In particular $\bar{\omega} = \omega^2 = \omega + 1$. Let $R_4 = \mathbb{F}_2 + \omega\mathbb{F}_2$ with the new equation for ω is $\omega^2 + \omega = 0$. Notice that R_4 has two maximal ideals namely $\langle \omega \rangle$ and $\langle \omega + 1 \rangle$. Furthermore, one can show that $R_4/\langle \omega \rangle$ and $R_4/\langle \omega + 1 \rangle$ are both isomorphic to \mathbb{F}_2 . The Chinese remainder theorem tells us that $R_4 = \langle \omega \rangle \oplus \langle \omega + 1 \rangle$. Therefore, $R_4 \simeq \mathbb{F}_2 \times \mathbb{F}_2$. The conjugate of ω is $\omega + 1$. Let \mathcal{R} be the field \mathbb{F}_4 if $\ell \equiv 3 \pmod{8}$ or the ring $R_4 \simeq \mathbb{F}_2 \times \mathbb{F}_2$ when $\ell \equiv 7 \pmod{8}$.

A linear code C of length n over \mathcal{R} is an \mathcal{R} -submodule of \mathcal{R}^n . The dual is defined as $C^\perp = \{u \in \mathcal{R} : u \cdot \bar{v} = 0 \text{ for all } v \in C\}$. If $C = C^\perp$ then C is self-dual.

We define $\Lambda_\ell(C) := \{x \in \mathcal{O}_K^n : \rho_\ell(x) \in C\}$ where $\rho_\ell : \mathcal{O}_K \rightarrow \mathcal{O}_K/2\mathcal{O}_K \rightarrow \mathcal{R}$. In other words, $\Lambda_\ell(C)$ consists of all vectors in \mathcal{O}_K^n which when taken mod $2\mathcal{O}_K$ componentwise are in $\rho_\ell^{-1}(C)$. The following is immediate.

Lemma 2. (1) $\Lambda_\ell(C)$ is an \mathcal{O}_K -lattice.
(2) $\Lambda_\ell(C^\perp) = 2\Lambda_\ell(C)^*$.
(3) C is self dual if and only if $\frac{\Lambda_\ell(C)}{\sqrt{2}}$ is self dual.

Let $u = (u_1, u_2, \dots, u_n) \in \mathcal{R}^n$ be a codeword and $\alpha \in \mathcal{R}$. Then the counting function $n_\alpha(u)$ is defined as the number of elements in the set $\{j : u_j = \alpha\}$. For a code C we define the complete weight enumerator (*cwe*), symmetrized weight enumerator (*swe*) and Hamming weight enumerator (*W*) to be

$$(3.1) \quad \begin{aligned} \text{cwe}_C(X, Y, Z, W) &:= \sum_{u \in C} X^{n_0(u)} Y^{n_1(u)} Z^{n_\omega(u)} W^{n_{1+\omega}(u)} \\ \text{swe}_C(X, Y, Z) &:= \text{cwe}_C(X, Y, Z, Z) \\ W_C(X, Y) &:= \text{swe}_C(X, Y, Y). \end{aligned}$$

Then we have the following.

Proposition 1. Let $\ell \equiv 3 \pmod{4}$, C be a linear code over \mathcal{R} , and $\frac{\Lambda_\ell(C)}{\sqrt{2}}$ be a Hermitian lattice constructed via the construction A. Then

$$(3.2) \quad \theta_{\Lambda_\ell(C)}(\tau) = \text{swe}_C(A_d(q), C_d(q), G_d(q))$$

where $A_d(q)$, $C_d(q)$, and $G_d(q)$ are given as in Eq. (2.4).

For a proof of the above statement the reader can see [1]. From the definition of one dimensional theta series we have

$$\theta_2(q) = 2q^{1/4} \sum_{i \in S} q^i, \quad \theta_2(q^4) = 2q \sum_{i: \text{odd}} q^{i^2-1}, \quad \theta_3(q^4) = 1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)},$$

where $S = \left\{ \frac{j^2-1}{4} : j \equiv 1 \pmod{2} \right\}$. From Eq. (2.4) we can write

$$G_d(q) = \frac{\theta_2(q)\theta_2(q^\ell)}{2} = q^{\frac{(\ell+1)}{4}} \alpha_1,$$

where $\alpha_1 = \sum_{i \in S} q^i \sum_{j \in S} q^{\ell j}$. Then,

$$\begin{aligned} A_d(q) &= \theta_3(q^4)\theta_3(q^{4\ell}) + \theta_2(q^4)\theta_2(q^{4\ell}) \\ &= (1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)})(1 + 2q^{4\ell} \sum_{j \in \mathbb{Z}^+} q^{4\ell(j^2-1)}) \\ &\quad + 4q^{\ell+1} \sum_{i: \text{odd}} q^{i^2-1} \sum_{j: \text{odd}} q^{(j^2-1)\ell} \\ &= \alpha_2 + q^{\ell+1}\alpha_3 + q^{4\ell}\alpha_4, \end{aligned}$$

where α_2, α_3 and α_4 have the following forms

$$\begin{aligned}\alpha_2 &= 1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)} \\ \alpha_3 &= 4 \sum_{i: \text{odd}} q^{i^2-1} \sum_{j: \text{odd}} q^{(j^2-1)\ell} \\ \alpha_4 &= 2 \sum_{j \in \mathbb{Z}^+} q^{4\ell(i^2-1)} (1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)}).\end{aligned}$$

Furthermore,

$$\begin{aligned}C_d(q) &= \theta_2(q^4)\theta_3(q^{4\ell}) + \theta_3(q^4)\theta_2(q^{4\ell}) \\ &= 2q \sum_{i: \text{odd}} q^{i^2-1} (1 + 2q^{4\ell} \sum_{i \in \mathbb{Z}^+} q^{4\ell(i^2-1)}) \\ &\quad + (1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)}) (2q^\ell \sum_{i: \text{odd}} q^{(i^2-1)\ell}) \\ &= \alpha_5 + q^\ell \alpha_6 + q^{4\ell+1} \alpha_7,\end{aligned}$$

where α_5, α_6 and α_7 have the following forms

$$\begin{aligned}\alpha_5 &= 2 \sum_{i: \text{odd}} q^{i^2-1} \\ \alpha_6 &= 2 \sum_{j: \text{odd}} q^{(j^2-1)\ell} (1 + 2q^4 \sum_{i \in \mathbb{Z}^+} q^{4(i^2-1)}) \\ \alpha_7 &= 4 \sum_{i: \text{odd}} q^{i^2-1} \sum_{j \in \mathbb{Z}^+} q^{4\ell(j^2-1)}.\end{aligned}$$

The next result shows that for large enough admissible ℓ and ℓ' the theta functions $\Theta_{\Lambda_\ell}(C)$ and $\Theta_{\Lambda_{\ell'}}(C)$ are virtually the same.

Theorem 1. *Let C be a code defined over R . For all admissible ℓ, ℓ' such that $\ell > \ell'$, the following holds*

$$(3.3) \quad \Theta_{\Lambda_\ell}(C) = \Theta_{\Lambda_{\ell'}}(C) + \mathcal{O}(q^{\frac{\ell'+1}{4}}).$$

Proof. Let

$$swe_C(X, Y, Z) = \sum_{i+j+k=n} a_{i,j,k} \cdot X^i Y^j Z^k$$

be a degree n polynomial. Write this as a polynomial in Z . Then

$$swe_C(Z) = \sum_{k=0}^n L_k Z^k = L_0 + Z \left(\sum_{k=1}^n L_k Z^{k-1} \right).$$

Terms in L_0 are of the form of $a_{i,j} X^i Y^j$, where $i + j = n$. From the above we have

$$\begin{aligned}A_d(q)^i \cdot C_d(q)^j &= (\alpha_2 + q^{\ell+1} \alpha_3 + q^{4\ell} \alpha_4)^i \cdot (\alpha_5 + q^\ell \alpha_6 + q^{4\ell+1} \alpha_7)^j \\ &= (\text{terms independent from } \ell) + q^\ell (\dots)\end{aligned}$$

Also we have seen that $G_d(q) = q^{(\ell+1)/4} \alpha_1$. This gives

$$\begin{aligned}\Theta_{\Lambda_\ell}(C) &= swe_C(A_d(q), C_d(q), G_d(q)) \\ &= (\text{terms independent from } \ell) + \mathcal{O}(q^{\frac{\ell+1}{4}}).\end{aligned}$$

Then the result follows. \square

Example 1. Let C be a code defined over R_4 which has symmetrized weight enumerator

$$swe_C(X, Y, Z) = X^3 + X^2Z + XY^2 + 2XZ^2 + Y^2Z + 2Z^3.$$

Then we have the following:

$$\begin{aligned} \Theta_{\Lambda_{63}}(C) &= 1 + 6q^4 + 12q^8 + 8q^{12} + 12q^{16} + 6q^{18} + 48q^{20} + 30q^{22} + \dots \\ (3.4) \quad \Theta_{\Lambda_{79}}(C) &= 1 + 6q^4 + 12q^8 + 8q^{12} + 6q^{16} + 30q^{20} + 6q^{22} + 48q^{24} + \dots \\ \Theta_{\Lambda_{79}}(C) &= \Theta_{\Lambda_{63}}(C) + \mathcal{O}(q^{16}). \end{aligned}$$

4. A FAMILY OF CODES CORRESPONDING TO THE SAME THETA FUNCTION

If we are given the code over \mathcal{R} and its symmetrized weight enumerator polynomial, then by Eq. (3.2) we can find the theta function of the lattice constructed from the code by using the construction A . Now, we would like to give a way to construct families of codes corresponding to the same theta function.

Let $\Theta(q) = \sum_{i=0}^{\infty} \lambda_i q^i$ be an acceptable theta series for level ℓ and

$$f(x, y, z) = \sum_{i+j+k=n} c_{i,j,k} x^i y^j z^k$$

be a degree n generic ternary homogeneous polynomial. We want to find out how many polynomials $f(x, y, z)$ correspond to $\Theta(q)$ for a fixed ℓ .

We have the following lemma.

Lemma 3. Let C be a code of size n defined over \mathcal{R} and $\Theta(q)$ be its theta function for level ℓ . Then, $\Theta(q)$ is uniquely determined by its first $\frac{n(\ell+1)}{4}$ coefficients.

Proof. Let C be a code over \mathcal{R} , $\Theta(q) = \sum_{i=0}^{\infty} \lambda_i q^i$ be its theta series, $s = \frac{n(\ell+1)}{4}$ and

$$f(x, y, z) = \sum_{i+j+k=n} c_{i,j,k} x^i y^j z^k$$

be a degree n generic ternary homogeneous polynomial. Find $A_d(q), C_d(q), G_d(q)$ for the given ℓ and substitute in $f(x, y, z)$. Hence $f(x, y, z)$ is now written as a series in q . Recall that a generic degree n ternary polynomial has $r = \frac{(n+1)(n+2)}{2}$ coefficients. So, the corresponding coefficients of the two sides of the equation are equal:

$$f(A_d(q), C_d(q), G_d(q)) = \sum_{i=0}^{\infty} \lambda_i q^i.$$

Consider the term

$$c_{i,j,k} (\alpha_2 + q^{\ell+1} \alpha_3 + q^{4\ell} \alpha_4)^i (\alpha_5 + q^{\ell} \alpha_6 + q^{4\ell+1} \alpha_7)^j (q^{\frac{(\ell+1)}{4}} \alpha_1)^k.$$

Then $c_{i,j,k}$ appears first as a coefficient of $q^{j+\frac{k(\ell+1)}{4}}$. For all such j, k we have $j + \frac{k(\ell+1)}{4} \leq \frac{n(\ell+1)}{4}$. Consider the equations where $c_{i,j,k}$ appears first. This is a system of equations with $\leq \frac{(n+1)(n+2)}{2}$ equations. Let us denote this system of equations as Ξ . Solve this system for $c_{i,j,k}$. Hence, $c_{i,j,k}$ is a function of l_0, \dots, l_s . For each $\mu > s$, l_{μ} is a function of $c_{i,j,k}$ for $i, j, k = 0, \dots, n$, and therefore a rational function on l_0, \dots, l_s . This completes the proof. \square

Next we have the following theorem:

Theorem 2. *Let C be a code of size n defined over \mathcal{R} and $\Theta_{\Lambda_\ell}(C)$ be its corresponding theta function for level ℓ . Then the following hold:*

- i): For $\ell < \frac{2(n+1)(n+2)}{n} - 1$ there is a δ -dimensional family of symmetrized weight enumerator polynomials corresponding to $\Theta_{\Lambda_\ell}(C)$, where $\delta \geq \frac{(n+1)(n+2)}{2} - \frac{n(\ell+1)}{4} - 1$
- ii): For $\ell \geq \frac{2(n+1)(n+2)}{n} - 1$ and $n < \frac{\ell+1}{4}$ there is a unique symmetrized weight enumerator polynomial which corresponds to $\Theta_{\Lambda_\ell}(C)$.

Proof. We want to find out how many polynomials $f(x, y, z)$ correspond to $\Theta_{\Lambda_\ell}(C)$ for a fixed ℓ . $\Theta_{\Lambda_\ell}(C)$ and $f(x, y, z)$ are defined as above. Consider the system of equations Ξ .

If $\frac{n(\ell+1)}{4} < r$ then our system has more variables than equations. Since the system is linear, the solution space is a family of positive dimension.

If $\frac{n(\ell+1)}{4} \geq r$ then for each equation in Ξ (see the proof of the previous Lemma) we have only one $c_{i,j,k}$ appearing for the first time. Otherwise suppose $c_{i,j,k}$ and $c_{i',j',k'}$ appear for the first time in an equation of Ξ . Then $j + \frac{k(\ell+1)}{4} = j' + \frac{k'(\ell+1)}{4}$. This implies

$$(4.1) \quad 4(j - j') = (k' - k)(\ell + 1).$$

Without loss of generality, assume $k' \geq k$. We can consider three cases.

case 1: If $k' - k \geq 2$, then from Eq. (4.1) we have $4n(j - j') = n(k' - k)(\ell + 1) \geq 4r(k' - k)$. Then we have $n(j - j') \geq (n + 1)(n + 2)$. Since $n \geq (j - j')$, we have a contradiction.

case 2: If $k' - k = 1$, then by Eq. (4.1) $j - j' = \frac{\ell+1}{4}$. Since $j - j' \leq n$ and $\frac{\ell+1}{4} > n$, we get a contradiction.

case 3: $k' - k = 0$, then by Eq. (4.1) we have $j = j'$. Hence $i = i'$.

Notice that $c_{n,0,0}$ is uniquely determined by the equation corresponding to the equation of coefficient of q^0 . Solve the system Ξ in the order of the equation that corresponds to the power of q . We have a unique solution for $c_{i,j,k}$. \square

4.1. Families of codes of length 3. In this section we discuss the codes of length 3 for different levels ℓ . Our main goal is to investigate the example provided in [1] and provide some computational evidence for the above two cases. We assume that the symmetrized weight enumerator polynomial is a generic homogenous polynomial of degree three.

Let $P(x, y, z)$ be a generic ternary cubic homogeneous polynomial given as below

$$(4.2) \quad \begin{aligned} P(x, y, z) = & c_1x^3 + c_2y^3 + c_3z^3 + c_4x^2y + c_5x^2z + c_6y^2x + c_7y^2z \\ & + c_8z^2x + c_9z^2y + c_{10}xyz. \end{aligned}$$

Assume that there is a code C , of length 3, defined over \mathcal{R} such that $swe_C(x, y, z) = P(x, y, z)$. First we have to fix the level ℓ . When we fix the level, we can find $A_d(q), C_d(q), G_d(q)$. By equating both sides of

$$p(A_d(q), C_d(q), G_d(q)) = \sum_{i=0}^{\infty} \lambda_i q^i,$$

we can get a system of equations. When $\ell = 7$, we are in the first case of the previous theorem. The system of equations is given by the following.

$$(4.3) \quad \begin{cases} c_1 - \lambda_0 = 0 \\ 2c_4 - \lambda_1 = 0 \\ 4c_6 + 2c_5 - \lambda_2 = 0 \\ 8c_2 + 4c_{10} - \lambda_3 = 0 \end{cases} \quad \begin{cases} 6c_1 + 4c_8 + 2c_5 + 8c_7 - \lambda_4 = 0 \\ 8c_4 + 8c_9 + 4c_{10} - \lambda_5 = 0 \\ 8c_5 + 8c_3 + 8c_7 + 8c_8 + 8c_6 - \lambda_6 = 0. \end{cases}$$

The solution for the above system is given by $c_1 = \lambda_0$, $c_4 = \frac{1}{2}\lambda_1$, and

$$(4.4) \quad \begin{aligned} c_2 &= \frac{1}{2}\lambda_1 + \frac{1}{8}\lambda_3 - \frac{1}{8}\lambda_5 + c_9, & c_3 &= \frac{3}{2}\lambda_0 - \frac{1}{4}\lambda_2 - \frac{1}{4}\lambda_4 + \frac{1}{8}\lambda_6 + c_7, \\ c_5 &= -3\lambda_0 + \frac{1}{2}\lambda_4 - 4c_7 - 2c_8, & c_6 &= \frac{3}{2}\lambda_0 + \frac{1}{4}\lambda_2 - \frac{1}{4}\lambda_4 + 2c_7 + c_8, \\ c_{10} &= -\lambda_1 + \frac{1}{4}\lambda_5 - 2c_9 \end{aligned}$$

where c_7, c_8, c_9 are free variables. By giving different triples (c_7, c_8, c_9) , we can construct different polynomials $P(x, y, z)$ for the same $\sum_{i=0}^{\infty} \lambda_i q^i$.

Consider the following theta function. From [1] there are two non isomorphic codes that give this theta function for level $\ell = 7$:

$$(4.5) \quad \Theta_{\sqrt{2}\mathcal{O}_{K_7^3}} = 1 + 6q^2 + 24q^4 + 56q^6 + 114q^8 + 168q^{10} + 280q^{12} + 294q^{14} + \dots$$

For this particular theta function, we can rewrite the solution (Eq. (4.4)) as follows: $c_1 = 1$, $c_2 = c_9$, $c_3 = 1 + c_7$, $c_4 = 0$, $c_5 = 9 - 4c_7 - 2c_8$, $c_6 = -3 - 2c_7 + c_8$, $c_{10} = -2c_9$.

For the triple $(1, 2, 0)$ (resp., $(0, 3, 0)$) we get the symmetrized weight enumerator polynomial for the code $C_{3,2}$ (resp. $C_{3,3}$). That is $swe_{C_{3,2}}(X, Y, Z) = X^3 + X^2Z + XY^2 + 2XZ^2 + Y^2Z + 2Z^3$ (resp., $swe_{C_{3,3}}(X, Y, Z) = X^3 + 3X^2Z + 3XZ^2 + Z^3$), where $C_{3,2}$ and $C_{3,3}$ are given by:

$$(4.6) \quad \begin{aligned} C_{3,2} &= \omega < [0, 1, 1] > + (\omega + 1) < [0, 1, 1] >^{\perp} \\ C_{3,3} &= \omega < [0, 0, 1] > + (\omega + 1) < [0, 0, 1] >^{\perp}. \end{aligned}$$

When $\ell = 15$, we are in the second case of the above theorem. The system of equations is as follows:

$$(4.7) \quad \begin{cases} c_1 - \lambda_0 = 0 \\ 2c_4 - \lambda_1 = 0 \\ 4c_6 - \lambda_2 = 0 \\ 8c_2 - \lambda_3 = 0 \\ 6c_1 + 2c_5 - \lambda_4 = 0 \end{cases} \quad \begin{cases} 8c_4 + 4c_{10} - \lambda_5 = 0 \\ 2c_5 + 8c_7 + 8c_6 - \lambda_6 = 0 \\ 4c_8 + 8c_7 + 12c_1 + 8c_5 - \lambda_8 = 0 \\ 10c_4 + 8c_9 + 8c_{10} - \lambda_9 = 0 \\ 8c_7 + 8c_5 + 12c_8 + 8c_3 + 8c_1 - \lambda_{12} = 0. \end{cases}$$

Each c_i appears first in exactly one equation. For example consider the seventh equation. c_7 is the only variable that appears first in the seventh equation. Solve the system in given order. The solution for the above system is given by; $c_1 = \lambda_0$, $c_2 = \frac{1}{8}\lambda_3$, $c_4 = \frac{1}{2}\lambda_1$, $c_6 = \frac{1}{4}\lambda_2$, and

$$(4.8) \quad \begin{aligned} c_3 &= -\lambda_0 - \frac{1}{2}\lambda_2 + \frac{3}{4}\lambda_4 + \frac{1}{4}\lambda_6 - \frac{3}{8}\lambda_8 + \frac{1}{8}\lambda_{12}, & c_5 &= -3\lambda_0 + \frac{1}{2}\lambda_4 \\ c_7 &= \frac{3}{4}\lambda_0 - \frac{1}{4}\lambda_2 - \frac{1}{8}\lambda_4 + \frac{1}{8}\lambda_6, & c_9 &= \frac{3}{8}\lambda_1 - \frac{1}{4}\lambda_5 + \frac{1}{8}\lambda_9 \\ c_8 &= \frac{3}{2}\lambda_0 + \frac{1}{2}\lambda_2 - \frac{3}{4}\lambda_4 - \frac{1}{4}\lambda_6 + \frac{1}{4}\lambda_8, & c_{10} &= -\lambda_1 + \frac{1}{4}\lambda_5 \end{aligned}$$

We have a unique solution. This implies that two non equivalent codes cannot give the same theta function for $\ell = 15$ and $n = 3$.

5. CONCLUDING REMARKS

The main goal of this paper was to find out how theta functions determine the codes over a ring of size 4. First we have shown how the theta functions of the same code C differ for different levels ℓ . The first $\frac{\ell+1}{4}$ terms of the theta functions for levels ℓ and ℓ' are the same, where $\ell' \geq \ell$.

In [1], two non-isomorphic codes that give the same theta function for level $\ell = 7$ but not under higher level constructions are given. We justified the reason why we don't have a similar situation for higher level constructions. In this note we have addressed a method that we can use for finding a family of polynomials that correspond to a given acceptable theta series for some fixed level ℓ . We have studied two cases depending upon ℓ that give either a positive dimensional family of polynomials or a unique polynomial.

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